A GIS-based vulnerability assessment of Pacific Northwest ports and harbors to tsunami hazards

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Abstract. Recent research suggests the Pacific Northwest could experience catastrophic earthquake and tsunami events in the near future, both from distant and local sources, posing a significant threat to coastal communities. Typically built on fill and located in low-lying areas prone to inundation, ports and harbors are especially vulnerable to these hazards. A collaborative, multi-year initiative is presently underway to increase the resiliency of Pacific Northwest ports and harbors to earthquake and tsunami hazards, involving Oregon Extension Sea Grant, Washington Sea Grant, the NOAA Coastal Services Center, and the USGS Center for Science Policy. As part of this initiative, a Geographic Information System (GIS) assessment model has been created, including 3-D system visualization, hazard scenario simulations, and resource vulnerability analyses. This vulnerability model will be reviewed, using the ports and harbors of Yaquina Bay, Oregon, as a case study. Analyses suggest that while the port and harbor area of Yaquina Bay will be greatly impacted by an event, it may need to be the primary site for community-wide relief and recovery operations. The model and subsequent analyses facilitate the development of site-specific strategies that protect port and harbor resources and provide a foundation for post-event planning.

1. Introduction

While the Pacific Northwest lacks recent catastrophic tsunami events, historical and geological evidence, such as Japanese historical tsunami documentation (Satake *et al.*, 1996) and tsunami sedimentation features (Atwater *et al.*, 1995), suggests the area has experienced them in the past and is likely to experience more in the near future. Based on this evidence, the last major tsunami-generating earthquake event in the Pacific Northwest occurred about 300 years ago, with an approximate M 8–9, at the interface of the North American and Juan de Fuca tectonic plates, commonly called the Cascadia Subduction Zone or CSZ (Satake *et al.*, 1996). Seismic activity along the CSZ is believed to have an average recurrence interval of 300 to 600 years, suggesting the Pacific Northwest is within the window of a catastrophic CSZ earthquake-generated tsunami event (Atwater and Hemphill-Haley, 1997). While teletsunamis also threaten Pacific Northwest coastal communities, they are considered outside the scope of this paper.

Tsunamis generated by CSZ earthquake events pose significant threats to Pacific Northwest coastal communities, including a great potential for life loss, damage and disruption of transportation and utility systems, industrial and commercial enterprises, and other development. Because of their

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geographic location, ports and harbors are especially vulnerable to these hazards. While ports and harbors constitute important economic and social components of coastal communities and recent studies have shown public perception of tsunami hazard issues is high along the Pacific Northwest coast (Cornutt, 1999), site-specific mitigation strategies for tsunami hazards have yet to be developed for these critical resources (CNHPWG, 1994).

Developing feasible mitigation strategies for tsunami hazards is a complex process that requires an understanding of both the physical attributes of an event and the socio-economic and physical attributes of a harbor community. To date, a great deal of research has gone into coseismic hazard assessment, such as potential CSZ tsunami inundation mapping (Priest, 1997), probabilistic ground motion maps (USGS, 2000), and loss estimation modeling, such as HAZUS97 (Risk Management Solutions, 1997). Community planning processes, such as FEMA's Project Impact (FEMA, 1997), provide frameworks for building disaster resiliency but lack specific, detailed tools to assess local vulnerability. While a great deal of work has focused on understanding tsunami hazards, no comprehensive vulnerability assessment tool presently exists at the community level. Past vulnerability assessments tend to be isolated endeavors that focus on specific resources, such as critical facilities (Charland, 1995). Recommendations to address vulnerability issues tend to be stand-alone guidelines or manuals (Urban Regional Research, 1988).

There is consensus that the Pacific Northwest is entering a window of potentially high risk to catastrophic tsunami events generated by CSZ earthquakes, and while ports and harbors are considered critical resources, tsunami mitigation strategies have yet to be developed. In addition, little has been done to develop vulnerability assessment methodologies or tools appropriate at the local level. This paper focuses on the development of a GIS-based tool that helps coastal communities assess their vulnerability to tsunami hazards.

2. Study Area

The port and harbor community of Yaquina Bay, Oregon, including the cities and port districts of Newport and Toledo, serves as the first demonstration site for the larger multi-agency research initiative. For the limited scope of this paper and poster presentation, the City and Port of Newport will be used to illustrate the development of the vulnerability tool. Located on the central Oregon coast, the Port of Newport is a deep draft port harbor serving a variety of vessels. The City of Newport is a community of over 9,000 residents and home to one of the largest fishing and fish processing industries on the West Coast. The Newport waterfront is characterized by a wide variety of commercial, industrial, and residential uses.

3. Methods

Faced with limited resources and competing priorities, decision-makers require accurate and accessible information when dealing with natural hazards issues. One of the greatest challenges in developing adequate information resources is interoperability, or the need to accommodate multiple users, data providers, hazard stages, scenario simulations, and mitigation goals. To address the issue of interoperability, the developed GIS tool will be housed within an online outreach and planning tool that caters to varying levels of expertise and data needs (http://www.csc.noaa.gov/products/tsunamis).

Another issue is the lack of hardware support for smaller communities. Unlike larger cities or academic institutions that may have incredible technical resources, smaller cities may be operating on a single personal computer. To address this issue, research focuses efforts on developing tools that can be performed on a single personal computer, utilizing internet-based information resources and online mapping applications to supplement the model. ArcView 3.2 is the primary GIS software and an ArcIMS, or Internet Map Server, project is being developed for those organizations and communities that do not have ArcView capabilities. In addition to the vulnerability model, GIS layers for individual port and harbor communities along the Oregon coast will be archived online. The GIS model is designed as a decision support tool, providing end users a framework and data structure to help them understand the various vulnerability issues their port and harbor may face. The intended goal of the model and vulnerability assessment process is to assist decision-makers in making their coastal community more disaster-resilient to tsunami hazards.

3.1 Working definitions

Because consensus on terminology has not been reached within the natural hazards community, it is important up front to distinguish between the various terms used in this project, as these terms serve as primary modules within the developed GIS model.

- *Hazard*: an extreme natural event that poses risks to human settlements (Deyle *et al.*, 1998). This term refers only to the physical attributes of the event, such as inundation potential or landslide potential.

- *Exposure*: the measure of a population at risk (Tobin and Montz, 1997). This term typically refers to the spatial coincidence of a resource (e.g., a structure) and a hazard (e.g., landslide potential). It is a spatial attribute and does not include the quality of the resource in question (e.g., building code level of a structure) or efforts already in place to minimize future losses (e.g., flood insurance, evacuation routes, foundation anchors).

- *Vulnerability*: a qualitative or quantitative examination of the exposure of some component of society or the environment (HJH Center, 2000).

The true vulnerability of a resource is a combination of hazards at a location, whether a resource is exposed to such hazards, and what has to be done to minimize future damages.

- *Risk*: the potential losses associated with a hazard, defined in terms of expected probability and frequency, exposure and consequences (FEMA, 1997). Risk assessment is the determination of the likelihood, or probability, of adverse impacts and is considered outside the scope of this research initiative. To truly assess risks, one must not only understand the physical event and built environment but also the community's economic setting, hazard perception and willingness to pay for mitigation options.

3.2 GIS model

It is not feasible to present the true extent of the developed GIS, such as query results or maps, within this paper. This is more appropriate in the poster presentation at the International Tsunami Symposium. Instead, this paper will focus on the general structure of the GIS model. It is important to emphasize that the GIS model is not designed to produce specific mitigation efforts (e.g., evacuation routes for a coastal community). Instead, it provides a map-based working environment and assembles relevant information to be used by the various local agencies, such as City Planning or County Emergency Services offices. The GIS system is organized around four main areas:

1. Portray the natural and human environment
2. Assess earthquake and tsunami hazards
3. Identify various resources exposed to hazards
4. Assess community vulnerability

3.2.1 GIS Level I: Portray the natural and human environment

The goal of this first section is to portray the natural and human environment in a digital context. It is a foundation on which future hazard and vulnerability layers are added. The majority of these layers can be found within online data warehouses. Exceptions to this were port-specific layers, such as docks, fueling facilities, and lifelines. GIS Level I layers include:

- *Visual Base Image*: USGS 7.5′ Digital Raster Graphs and Digital Orthophotoquads.
- *Natural Environment*: topography (10 m Digital Elevation Models), bathymetry, estuary habitats, geology, soils, zones of fill, rivers, lakes, critical/significant habitat
- *Human Environment*: roads, utility lifelines (potable water, waste water, natural gas, electrical power, telephone), structural footprint

(type, seismic assessment, occupancy rates, historical/cultural significance), port-specific structures, fueling facilities, docks/piers (floating vs. fixed docks, number/types of boat), dams, hazardous material, waterfront zoning, parcel maps, demographics, critical facilities.

3.2.2 GIS Level II: Assess earthquake and tsunami hazards

The goal of this section is to provide a spatial context to the hazards. Although the focus of this paper is tsunami hazards, it is also important to consider earthquake hazards. During an actual event, it will be the interaction of the various hazards that determines how extensive damage will be. For example, landslides, induced by the initial earthquake event, will generate debris that will then be transported elsewhere in the port and harbor by incoming tsunami waves. GIS Level II layers include:

- Liquefaction Potential
- Landslide Potential
- Amplification Potential
- Tsunami Vector Field
- Tsunami Inundation
- Tsunami Debris Potential
- Tsunami Maximum Heights
- Landslide Debris Potential

As mentioned in the introduction, the main scenario driving this analysis is a tsunami event generated by a M 8–9 earthquake along the Cascadia Subduction Zone. GIS layers showing the potential for liquefaction, landslides, ground shaking amplification, and tsunami inundation during such an event come from the Oregon Department of Geology and Mineral Industries (Madin and Wang, 1999). Maximum water level heights and current velocity data were offered by the Oregon Graduate Institute, in collaboration with the NOAA Pacific Marine Environmental Laboratory (Meyers, 2001). Tsunami and landslide debris potential layers were developed in collaboration with local stakeholders and various focus group meetings.

3.2.3 GIS Level III: Assess exposed resources

The goal of this section is to assess the exposure of community resources to earthquake-tsunami hazards. The level of exposure will depend on the severity and type of individual hazards, the summation of hazards at that site, and the resource exposed to the hazard. The GIS model can be further refined if local stakeholders are able to rank individual resources, with regards to economic and/or community value. Various subsections exist within this section, including: (1) societal analyses, (2) built environment analyses, (3) critical resource analyses, (4) infrastructure analyses, (5) economic analyses, and (6) environmental analyses. As mentioned before, analyses are primarily spatial correlations to determine which resources are in hazardous areas. Data for each subsection is a combination of the previously mentioned data layers in Section 3.2.1 and information generated by stakeholder input.

The types of GIS and stakeholder-based queries are too extensive to list here; instead, a few examples are presented to illustrate the need of stakeholder input. First, port and harbor communities are known for having highly transient populations, including seasonal fishing fleets and tourists. To truly understand the vulnerability of human populations within a coastal community, it is important to understand how and where these populations fluctuate—information that the U.S. Census cannot capture. For instance, relief and recovery plans for the Oregon Aquarium, an aquarium along the Newport waterfront, must not only include elements for workers and creatures but for the potential of over 5,000 tourists if a tsunami occurs during the summer. Second, typical built environment analyses focus on the integrity of the individual structure. Within this model, stakeholders are asked to go further by identifying "critical resources." These resources are those that are deemed critical by the community for conducting response and recovery operations after a tsunami event and for the community's general physical, social, economic, and cultural well-being.

3.2.4 GIS Level IV: Assess community vulnerability

The goal of this section is to assist a port and harbor community in determining their ability in dealing with issues raised by the resource exposure assessment. The true vulnerability of a resource is a combination of the hazards the resource is exposed to, the present condition of the resource, and community efforts to lessen the impacts of the hazards. Potential efforts are only suggestions and it is up to individual organizations and the community as a whole to decide on efforts appropriate to their area. This section is organized as a series of checklists or questions, depending on the resource in question, with a Visual Basic interface.

Again, the limited nature of this paper does not allow for a complete overview of the various vulnerability issues. Examples presented here focus on the vulnerability of port and harbor populations and structures. First, for a certain segment of a port and harbor community, stakeholders should determine if adequate evacuation routes for populations at risk have been developed, including both land and water-based populations. In addition, the community's ability to shelter displaced populations and to provide relief supplies to displaced populations, including supply source routes and staging areas, should be determined. With regard to the built environment, the true vulnerability of a structure would be a function of its construction, its location within the community, and the following additional conditions:

- *Pre-event condition*: structure is either built to current Uniform Building Code standards or has been retrofitted; the structure is bolted to its foundation.

- *Response Issues*: the existence of automatic shut-off valves.

- *Recovery Issues*: building owners have earthquake or flood insurance, and/or a recovery plan.

4. Preliminary Findings

Initial GIS queries, to be visually presented at the International Tsunami Symposium, suggest the Newport, Oregon area could be severely impacted by a CSZ earthquake-induced tsunami event. Ground shaking from the earthquake, with estimated peak ground accelerations of 0.3 g, will induce massive landslides and major liquefaction in the port and harbor area. Tsunami water level heights could be on the order of 5 m above mean sea level within the port area. Resources exposed to significant water levels include the entire Port of Newport, numerous hotels and residences, the Oregon Aquarium, and the Hatfield Marine Science Center.

While research is still in an early stage of development, preliminary comments can be made from feedback garnered from a series of technical workshops and stakeholder focus groups held in Newport over the past year. First, information presently available to decision-makers is not perceived as adequate to support coastal hazard strategy development. Available information, such as published maps and reports, are not presently being used to assist strategy development. Second, product development must recognize limited human and technological resources of decision-makers. Developed models must be simple enough for quick comprehension but robust enough to provide service in decision support environments.

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